

Suppression of inelastic electron-electron scattering in Anderson Insulators

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Abstract

We report on measurements of absorption from applied ac fields in Anderson-localized indium-oxide films. The absorption shows a roll-off at a frequency that is much smaller than the electron-electron scattering rate measured at the same temperature in diffusive samples of this material. These results are interpreted as evidence for discreteness of the energy spectrum.

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Inelastic scatterings of electrons play an important role in the properties of Fermi gas systems. The most frequently encountered types of such events are electron-electron (e-e) and electron-phonon (e-ph) scatterings. Energy-exchange via efficient e-e scattering is vital for establishing the Fermi-Dirac distribution, which defines the electron temperature. The electron-phonon inelastic collisions are needed to maintain steady-state situations, and in particular, are responsible for the validity of Ohms law. Either process may lead to de-coherence of the electrons and thus control the quantum effects exhibited by the system.

Both, the e-e inelastic-rate γ_{in}^{e-e} , and the e-ph inelastic-rate γ_{in}^{e-ph} , are temperature dependent. The specific form of these rates (typically a power-law of the temperature T), depend on system dimensionality, temperature range, and the type and degree of disorder. In the thermodynamic limit of diffusive systems however, and at low, yet experimentally accessible, temperatures, γ_{in}^{e-e} is usually larger than γ_{in}^{e-ph} [1].

In this Letter we report on measurements of the energy absorbed by the charge-carriers in Anderson localized indium-oxide films from electric fields as function of frequency f . The technique used in this work utilizes a unique property of electron-glasses [2]; the excess-conductance produced by a non-Ohmic field reflects the energy absorbed by the charge carriers. This technique allows a measurement on systems with very small volume, sensitive enough to allow for weak absorption from electric fields, and most important for this work - can be carried over a large frequency range.

The measurements described below suggest that γ_{in}^{e-e} in the electron-glass is dramatically suppressed relative to its value at the diffusive regime of the same material, and thermalization of the electronic system is presumably governed by γ_{in}^{e-ph} . These results may be relevant for testing many-body localization models [3, 4].

The electron-glass samples used in this study were thin films of crystalline indium-oxide ($\text{In}_2\text{O}_{3-x}$) e-gun evaporated on glass substrates. Lateral size of the samples used here were $L = 2$ mm long and $W = 1$ mm wide. Their thickness ($d = 52$ Å) and stoichiometry (fine-tuned by UV-treatment [5]) were chosen such that at the measurement temperatures, the samples had sheet resistance R_{\square} in the

range $6 \text{ M}\Omega$ - $12 \text{ M}\Omega$. Conductivity of the samples was measured using a two terminal ac technique employing a 1211-ITHACO current preamplifier and a PAR-124A lock-in amplifier. The measurements were performed with the samples immersed in liquid helium at $T=4.11$ K held by a 100 liters storage-dewar. This made it possible to perform measurements of samples while maintaining a stable bath-temperature over the very long period required for the type of experiments described below. Fuller details of sample preparation, characterization, and measurements techniques are given elsewhere [6, 7].

Several sources were used for exciting the system by non-Ohmic fields; the internal oscillator of the PAR124A (up to 2 kHz and 10 Vrms) (Fluke PM5138A (dc and up to 10 MHz and 40 Vpp), and Tabor WS8101 (up to 100 MHz and 16 Vpp).

The main technique used in this study is the ‘stress-protocol’ previously used in aging experiments [8]. The procedure is composed of the following stages: After the sample is equilibrated at the measuring temperature (typically for 20 hours), its conductance G versus time is recorded while keeping the electric field $F=F_0$ small enough to be as close to the Ohmic regime as possible. This defines a baseline ‘equilibrium’ conductance $G(F_0)$. Next, F is switched to a non-Ohmic F_s which causes the conductance to increase by a predetermined $\Delta G(0)$. F_s is kept on the sample for a time t_w , then the field is switched back to F_0 and the conductance is continued to be measured for $\approx 5 \cdot t_w$. This last stage is depicted in figure 1 as a relaxation of G towards the equilibrium $G(F_0)$ with a logarithmic law characteristic of relaxation processes of electron-glasses [2]. A measure of the magnitude of the excess conductance that results from the stress is δG_{rel} , defined by extrapolating $\delta G(t)$ to 1 second as illustrated in the inset to Fig. 1. $\delta G(t)$ is $G(F_0, t) - G(F_0)$ where the origin of time t is taken as t_w+1 (i.e., 1 second after F_s is reset to F_0).

The relaxation of $\delta G(t)$ reflects the release of excess energy accumulated during t_w through Joule-heating produced by the field; While F_s is on, the energy absorbed by the electronic system gives rise to an excess phonons within the sample, making it somewhat ‘hotter’ than the bath. A steady-state is established by the flow of energy

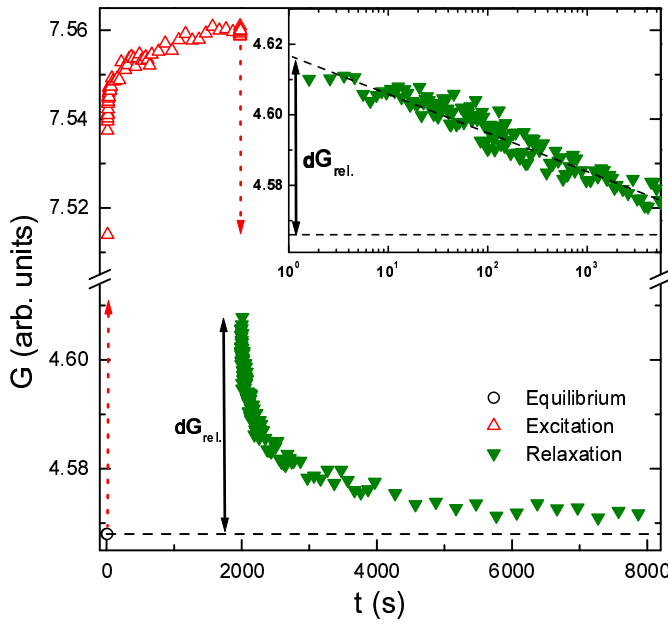


FIG. 1: Conductance versus time $G(t)$ illustrating a typical ‘stress-protocol’ run. The sample is $\text{In}_2\text{O}_{3-x}$ film with an equilibrium $R_{\square}=12.5 \text{ M}\Omega$ measured at $T=4.1\text{K}$ with $F_0=5 \text{ V/m}$ and $F_s=500 \text{ V/m}$ both at 730 Hz . The inset shows the logarithmic relaxation of $\delta G(t)$ and the definition of δG_{rel} (upper plot). Dashed lines delineate the equilibrium conductance $G(F_0)$.

from the sample-phonons into the thermal-bath. The increased density of high energy phonons (over the phonon population in equilibrium at the bath temperature), randomizes the charge configuration of the electron-glass in a similar vein that raising the bath-temperature would [9]. This is reflected in the sluggish conductance increase during t_w , and to the ensuing $\delta G(t)$ after the stress is relieved (Fig.1). δG_{rel} is used here as a *relative* measure of the energy absorbed by the electronic system from the stress field (i.e., no quantitative value is assigned to this measure, which, as will be clear below, does not affect our conclusions).

The intriguing finding of this work is the non-trivial dependence of δG_{rel} on the frequency of the stress field. In these experiments, the stress-protocol is repeated using fields $F_s(f)$ of different frequencies f as described next.

For a meaningful comparison between results of different frequencies, $F_s(f)$ is applied for the same t_w and its amplitude chosen such as to affect the *same* $\Delta G(0)$ for each f . This procedure then requires a pre-knowledge of the F_s amplitude that achieves the target $\Delta G(0)$. This is obtained from plots of $G(F)$ taken independently at each frequency to be measured. Examples of $G(F)$ plots measured at different frequencies are shown in figure 2.

These plots were used in the first series of the stress-protocol experiments where $\Delta G(0)/G(F_0)$ was set to be 0.75 ± 0.2 at all frequencies using a sample with Ohmic

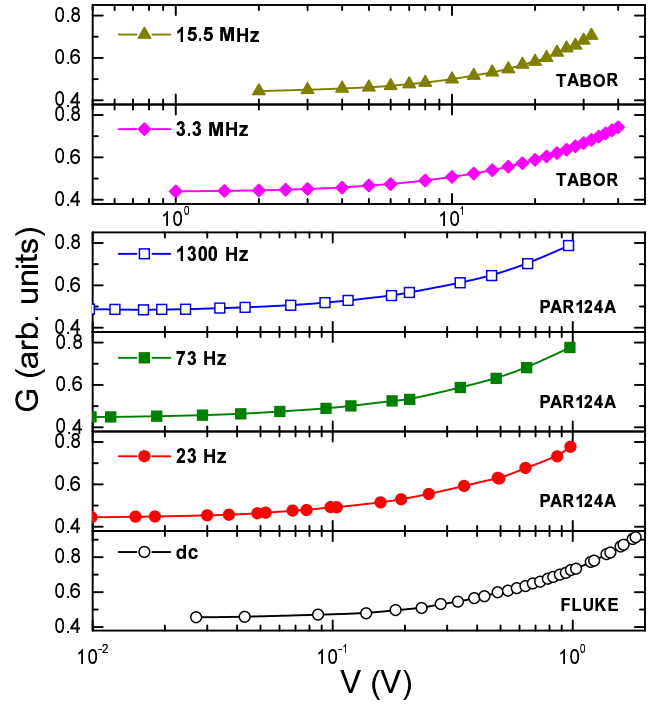


FIG. 2: The dependence of the sample conductance on the applied voltage measured at different frequencies. The instrument used as the voltage source for a given plot is marked on the bottom right corner.

conduction (per-square) $G(F_0)=8.33 \cdot 10^{-8} \Omega^{-1}$. Note that the functional dependence of these $G(V)$ curves is only weakly dependent on the frequency of the measurement. The δG_{rel} that results from the stress protocol at these frequencies, on the other hand, *is frequency dependent* (figure 3): It is essentially constant (actually, starting from dc which cannot be explicitly shown on Fig. 3) up to some frequency, then it gradually rolls-off, and tends to vanish for $f \geq 10^8 \text{ Hz}$. Note that this is consistent with the lack of absorption at the microwaves frequencies reported previously [7].

Also shown in Fig. 3 are the respective results of another sample with Ohmic conduction (per-square at 4.1K) $G(F_0)=1.64 \cdot 10^{-7} \Omega^{-1}$. This sample was obtained from the first by UV-treatment, which amounts to a small change of stoichiometry [5]. The two samples have therefore identical geometry, and crystallites-size. They differ in their $G(F_0)$, in their localization length ξ (c.f., Fig. 4 below), and in that $\Delta G(0)/G_0$ was set to be 0.65 ± 0.2 for the second sample. To achieve the targeted $\Delta G(0)/G_0$, the applied voltages during t_w ($1400 \pm 10 \text{ sec}$ for both samples), were 1 V(rms) and 0.5 V(rms) for the first and second samples respectively.

The linearity of δG_{rel} with $\Delta G(0)$ was ascertained by measuring δG_{rel} at half and twice of the nominal $\Delta G(0)$ of the series and for both: $f=23 \text{ Hz}$ and $f=0.8 \text{ MHz}$. It should also be noted that to achieve a constant $\Delta G(0)$

higher frequencies the field amplitudes across the sample were, if anything, somewhat larger than at low frequencies. Therefore the vanishing values of δG_{rel} at high frequencies cannot be due to spurious effects; the sample and its environment (substrate etc.) are the same at all stress frequencies. Also, at the higher frequencies, where δG_{rel} is diminishing with f , the electrons are subjected to as large or even larger field amplitudes than used at low frequencies to get the same $\Delta G(0)$.

The roll-off frequency of $\delta G_{rel}(f)$ turns out to be of the order of the rate by which energy acquired from the field is dissipated into the bath (presumably, γ_{in}^{e-ph}); Under a bias voltage V (dc or low enough f), acting on resistance $R(V)$, the following expression may be used to estimate the rate of dissipated energy in a steady state:

$$\frac{V^2}{R(V)} = C_{el}(T)(\Delta T)\tau_{in}^{-1} \quad (1)$$

Here C_{el} is the electronic heat-capacity, ΔT is the temperature difference between the electronic system and the phonons, and τ_{in}^{-1} is the rate of energy dissipation. We shall use the free-electron expression: $\frac{2}{3}\pi^2 N(0)k_B^2 T u$ for $C_{el}(T)$, where $N(0) \simeq 2 \cdot 10^{45} \text{ J}^{-1} \text{ m}^{-3}$ is the thermodynamic density of states at the Fermi energy for $\text{In}_2\text{O}_{3-x}$ [5], and $u = L W d$ is the sample volume ($u = 1.04 \cdot 10^{-14} \text{ m}^3$ for our samples). To get a rough estimate for ΔT we neglect the difference in temperature between the system and the phonons of the thermal bath, and assume that the conductance of the sample versus temperature (measured under near-Ohmic conditions), reflects the electron temperature [10]. The temperature dependence of G_0 is shown in figure 4 for the two samples. Using these data gives for $\Delta T = 0.71 \text{ K}$ for the first sample, and $\Delta T = 0.74 \text{ K}$ for the second sample, which from Eq. 1 we get $\tau_{in}^{-1} = 3.5 \cdot 10^5$ and $7.1 \cdot 10^5 \text{ Hz}$ respectively. These rates are somewhat under-estimated for two reasons; disregarding the elevated temperature of the system-phonons, and assuming that the only source for $\Delta G(0)$ is ‘heating’ (i.e., neglecting the field-assisted hopping contribution [11]). These omissions overestimate ΔT and thus lead to an underestimated rates by about an order of magnitude [12], still within the region where δG_{rel} decays which extends over nearly four decades, presumably reflecting the distribution of γ_{in}^{e-ph} . By comparison, the excess conductance in these electron-glasses has been observed to relax over at least six decades in time, and the logarithmic law of this relaxation is suggestive of a wide rate-distribution. Wide rate-distributions are ubiquitous in condensed matter systems, and invariably the underlying reason is disorder. This is a natural occurrence in hopping conductivity; in a realistic system the localization length ξ is distributed over a range determined by the strength (and type) of the quenched disorder. Electronic transition probabilities depend on wave-function overlap, and even on a single-particle level, a mildly wide ξ -distribution may translate into an exponentially wide distribution. This complication may be ignored

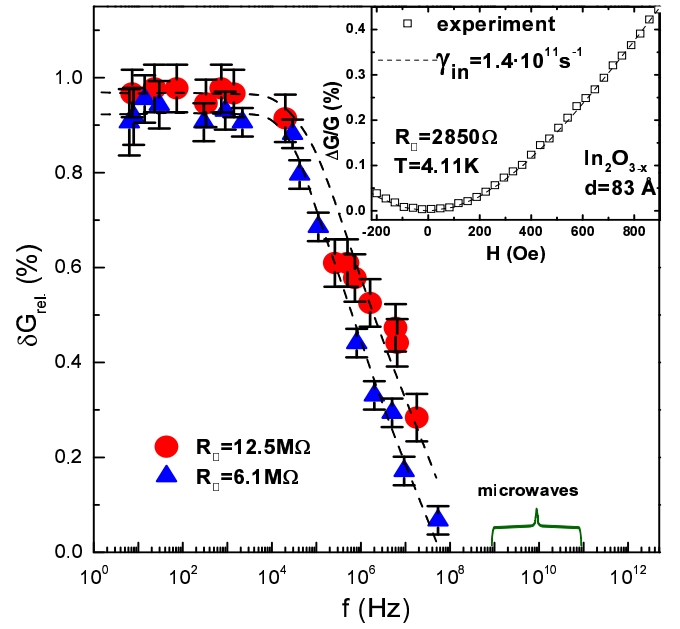


FIG. 3: The frequency dependence of the amplitude of excess conductance following the stress protocol for the two studied samples (see text for details). Dashed lines are guides for the eye. The inset depicts a magneto-conductance measurement for a diffusive film of the same material fitted to the weak-localization theory of Ref. [10].

when dealing with the macroscopic conductance due to its percolative nature but it should be evident in energy relaxation processes.

The inability of the electrons to absorb energy from the field is expected when the drive frequency exceeds γ_{in}^{max} , the maximum rate of their energy-exchange with any available sub-system. In the diffusive regime, γ_{in}^{max} is the electron-electron inelastic rate γ_{in}^{e-e} which at low temperatures, is much larger than the electron-phonon inelastic rate γ_{in}^{e-ph} . This, in particular, holds true for $\text{In}_2\text{O}_{3-x}$ that has uncommonly high Debye temperature (1050-1100 K [13]) and thus relatively low γ_{in}^{e-ph} in line with the above estimate of $\approx 10^6 \text{ sec}^{-1}$ at $\approx 4 \text{ K}$. The e-e inelastic rate in a two-dimensional (2D) $\text{In}_2\text{O}_{3-x}$ film with $R_{\square} \approx 10^3 \Omega$ at $\approx 4 \text{ K}$ is of the order of $\gamma_{in}^{e-e} \approx 10^{11} \text{ sec}^{-1}$. This is based on magneto-conductance measurements and a fit to the weak-localization theory [14]. An example is shown in the inset to Fig. 3. The dephasing rate $\gamma_{in} \approx 1.4 \cdot 10^{11} \text{ sec}^{-1}$, that results from the fit to the theory, is consistent with the Abrahams et al model for e-e inelastic rate [15]. In the diffusive regime and for thin films the theory anticipates that γ_{in}^{e-e} should only *increase* with disorder. Our experiments suggest that, for sufficiently strong disorder, this trend has been reversed; γ_{in}^{e-e} in both films is smaller than its value in the $R_{\square} \approx 3 \text{ k}\Omega$ sample by *at least* three orders of magnitude: Note that the technique used here can only put an upper bound on the inelastic rate; it cannot determine the ac-

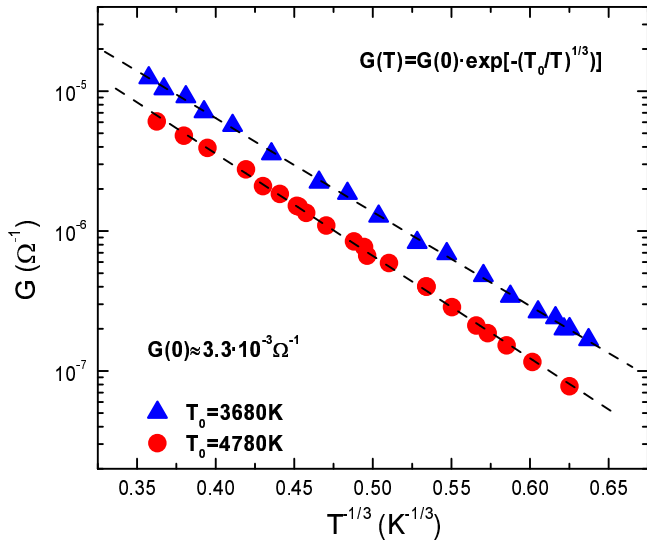


FIG. 4: Temperature dependence of the conductance of the samples used in this work and their relevant parameters derived from the plots.

tual γ_{in}^{e-e} , which might in fact be much smaller than γ_{in}^{\max} estimated from the roll-off in Fig. 3.

This dramatic suppression in γ_{in}^{e-e} of the same material at ≈ 4 K is presumably related to the change in the transport mechanism, which in 2D $\text{In}_2\text{O}_{3-x}$ films with $R_{\square} \leq h/e^2$ is diffusive while sample with $R_{\square} \gg h/e^2$ exhibit variable-range-hopping (VRH). The samples studied here obey Mott's VRH in 2D, given by $G(T) = G(0) \cdot \exp\{(T_0/T)^{1/3}\}$ where $T_0 \approx [k_B N(0) \xi^2 d]^{-1}$ (Fig. 4). Over the temperature range relevant for our experiments the thermal energy is *much* smaller than the mean level-spacing $\delta = [N(0) \xi^2 d]^{-1}$. In a non-interacting picture, the inherent *discreteness* of the energy-spectrum of the system should be evident in the transport when $R_{\square} \gg h/e^2$ but it is washed-out due to life-time broadening in the limit $R_{\square} \leq h/e^2$ where the inelastic diffusion length is smaller than ξ . Discreteness is indeed the key to the orders-of-magnitude change in γ_{in}^{e-e} , and this may be understood in the following way:

In the simplest scenario, of independent set of electronic states localized over regions with spatial extent ξ , the problem is reduced to that of a quantum dot with volume $\xi^2 d$. This case has been studied [16] with the result that γ_{in}^{e-e} is exponentially suppressed once $k_B T \leq \delta$. For our samples δ is about three orders of magnitude larger than the temperature of the measurements, and therefore, γ_{in}^{e-e} should be vanishingly small. Energy exchange between electrons and their thermalization hinge on the existence of another sub-system with a continuous spectrum, e.g., the phonons bath. This single-particle scenario seems to be consistent with our data.

However, an Anderson insulator is not an independent set of quantum dots, and Coulomb interactions cannot be

ignored in such a disordered medium with its impaired screening. The samples studied here are electron-glasses, and electron-electron interactions manifestly play a crucial role in their transport properties [17].

A fundamental question in this context is whether many-body excitations could de-localize the system and render the energy spectrum continuous. These issues were considered by Anderson [18], Fleishman and Anderson [19], and recently by Gornyi et al [3], and Basko et al [4]. For short range interactions (and in a 2D system, lacking a mobility edge) the spectrum is expected to be discrete and thus, at low temperatures, electron can exchange energy among themselves only by virtue of the phonons bath (or another sub-system with a continuous spectrum). In other words, the rate of energy exchange between electrons is effectively limited by the electron-phonon inelastic rate γ_{in}^{e-ph} . Our results are also consistent with this, many-body scenario, which is physically more relevant for electron-glasses.

A corollary of many-body-localization is that, at low temperatures, the energy $\Delta \varepsilon_{ij}$ needed for an electron to hop from localized site i to localized site j , must be supplied by a continuous bath. Hopping models traditionally assumed that it is the electron-phonon interaction that is involved. However the magnitude of the pre-exponential factor of $G(T)$ (see, e.g., Fig. 4) and its weak temperature dependence have yet to be accounted for by a model based on a phonon-bath. Identifying the nature of the bath that meets the constraints implied by the many experiments published over the last four decades, as well as the one presented here, is a challenge for theory.

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